AD-A062 662   CALIFORNIA UNIV BERKELEY DEPT OF CHEMICAL ENGINEERING   F/G 7/4
MOLECULAR THEORY OF VISCOELASTICITY FOR HOMOGENEOUS BLOCK AND G--ETC(U)
DEC 78   D SOONG, M SHEN   N00014-75-C-0955

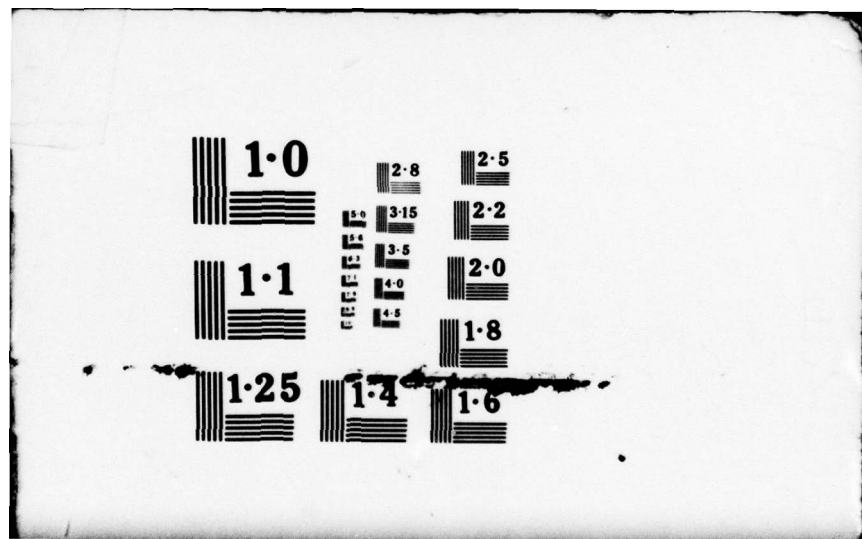UNCLASSIFIED   TR-22   NL

1 OF 1
ADA
062662

END
DATE
FILMED
3 -79
DDC

(12) **LEVEL** II

NU

(6) Molecular Theory of Viscoelasticity for
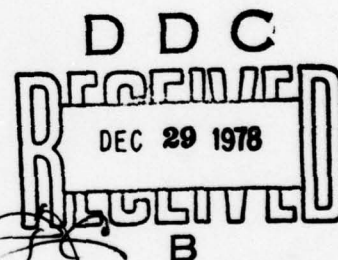
Homogeneous Block and Graft Copolymers.

by

(10) David Soong and Mitchel Shen

Department of Chemical Engineering
University of California
Berkeley, California 94720

(11) 1 Dec 78   (13) 29 p

December 1, 1978

(14) TR-22

D D C
RECEIVED
DEC 29 1978
B

(15) N00014-75-C-0955 *

78 12 26 029

404 601

Molecular Theory of Viscoelasticity for

Homogeneous Block and Graft Copolymers

by

David Soong and Mitchel Shen
Department of Chemical Engineering
University of California
Berkeley, California 94720

Abstract

The Rouse-Bueche-Zimm molecular theory of viscoelasticity
has been extended to compute the retardation time spectra of
radial block and graft copolymers of various configurations
and compositions. The basic assumption of the model is that the
effect of the presence of foreign blocks and grafts on the
retardation spectrum is due to the difference in the friction
coefficients. Mathematically this modification is accomplished
by introducing into the equations of motion a frictional co-
efficient matrix. Retardation spectra can then be obtained by
numerically solving for the eigenvalue spectrum on a computer.
Results show that the viscoelastic retardation spectra and
maximum retardation times of those copolymers vary as a function
of the number of side chains, their lengths and the spacings
between them. The model is restricted to bulk homogeneous co-
polymers, or those copolymers dissolved in appropriate solvents
without microphase separation.

1

78 12 26 029

Introduction

Block and graft copolymers exhibit interesting viscoelastic properties. Although most of these systems show microphase separation, some of them are homogeneous, even in bulk, e.g., the block copolymers of styrene and α-methyl styrene [1,2]. Block copolymers in appropriate solvents also show no microphase separation [3-5]. The molecular dynamics of these homogeneous copolymers may be treated on the basis of the bead-and-spring model enunciated by Rouse [6], Bueche [7], and Zimm [8]. This theory has previously been applied to block copolymers of different configurations and compositions [9-15]. In this paper, we extend the model to calculate the maximum relaxation times of graft copolymers and radial block copolymers. Viscoelastic relaxation times are computed numerically for these copolymers with different configurations.

Theory

Following the method of analysis used in the calculations of block copolymers [11], we adopt a simplified procedure first proposed by Peticolas [16]. The free-draining case of Rouse [6] and Bueche [7] is also used in our calculations.

The RBZ model represents the polymer molecule by $N+1$ beads held together with N entropy springs. In a velocity gradient, the springs are stretched. The spring constant is $3kT/b^2$ where b^2 is the mean square end-to-end distance of the submolecule. As the beads move through the medium, a viscous drag is exerted on them the magnitude of which is determined by the friction co-

efficient f. At the cessation of flow, the recovery of the polymer chain proceeds without acceleration, so that the viscous and the elastic forces are exactly equal to each other. The equation of motion for the string of identical beads is given in matrix notation as (1)

$$\dot{\underline{x}} = -\sigma \, \underline{Z} \, \underline{x}, \tag{1}$$

where $\underline{x}$ and $\dot{\underline{x}}$ are the column vectors of the bead position and the bead velocity respectively, $\underline{Z}$ is the nearest neighbor matrix and $\sigma = 3kT/\langle b_o^2 \rangle f$ in which $\langle b_o^2 \rangle$ is the mean square end-to-end distance and f is the frictional coefficient.

Eq. 1 was written for homopolymers. For graft copolymers, the equation must be modified to take into account the fact that not all beads are the same. Both the submolecular spring constants and the frictional coefficients of the beads are different (9). In addition, any bead connected to a graft point experiences elastic spring forces from all other beads immediately attached to the graft point and one other bead that is connected to this bead. To illustrate, bead k when disturbed from its equilibrium position (Figure 1) is pulled by three other beads, i,j,l. This gives the value 3 for the diagonal element (k,k) and -1 at off-diagonal positions (i,k), (k,i), (j,k), (k,j), (k,l), (l,k), of the nearest neighbor matrix $\underline{Z}$. The $\underline{Z}_g$ given below has 4's for some of its diagonal elements, because the matrix is written for graft copolymers with only one bead separating adjacent grafts. These beads are connected to four other beads, two on the grafts, the other two along the main chain. Thus, the resulting modified nearest neighbor matrix $\underline{Z}_g$ can be written as:

$$
\underset{\sim}{Z}_g =
\begin{bmatrix}
-1 & & & & & & & & & & & & \\
-1 & 2 & -1 & & & & & & & \mathbf{0} & & & \\
 & -1 & 2 & -1 & & & & & & & & & \\
 & & -1 & 3 & 0 & & & & & & & & \\
 & & & 0 & -1 & -1 & & & & & & & \\
 & & & & -1 & 2 & -1 & & & & & & \\
 & & & & & -1 & 2 & -1 & & & & & \\
 & & & & & & -1 & 3 & -1 & & & & \\
 & & & & & & & -1 & 4 & 0 & & & \\
 & & & & & & & & 0 & -1 & 2 & -1 & \\
 & \mathbf{0} & & & & & & & & -1 & 2 & -1 & \\
 & & & & & & & & & & -1 & 3 & -1 \\
 & & & & & & & & & & & -1 & 2
\end{bmatrix}
$$

For a graft copolymer consisting of side chains of polymer A, and a main chain of polymer B with frictional coefficients f_A, f_B, respectively, the equations of motion become:

$$\dot{\underline{x}} = -\sigma_B \underline{D}^{-1} \underline{Z}_g \underline{x}, \tag{2}$$

where $\sigma_B = 3kT/b^2 f_B$. $\underline{D}^{-1}$ is the inverse of a diagonal matrix $\underline{D}$ whose elements are the frictional coefficients of the corresponding beads divided by those of B beads. For example,

$$\underline{D} = \begin{bmatrix} 1_1 & & & & \\ & \ddots & & & \\ & & \delta_A \delta_A 1_1 & & \\ & & & \delta_A \delta_A & \\ & & & & \ddots \end{bmatrix} \tag{3}$$

where $\delta_A = b_A^2 f_A / b_B^2 f_B$, occurring at positions corresponding to the side chain beads. The $\underline{D}^{-1}\underline{Z}_g$ matrix is no longer a tridiagonal matrix.

To solve eq. 3., we define a new set of coordinates $\underline{r}$ related to $\underline{x}$ as follows:

$$\underline{r} = \underline{A}\,\underline{x}, \tag{4}$$

where the $\underline{A}$ matrix is defined by $\underline{Z}_g = \underline{A}^T \underline{A}$. Operating on both sides of eq. 4 with $\underline{A}$, it becomes

$$\dot{\underline{r}} = -\sigma_A\, \underline{A}\, \underline{D}^{-1}\, \underline{A}^T\, \underline{A}\, \underline{x} \tag{5}$$

$$= -\sigma_A\, \underline{S}\, \underline{r},$$

where

$$\underline{S} = \underline{A} \; \underline{D}^{-1} \; \underline{A}^T \qquad (6)$$

is a symmetrical tridiagonal NxN matrix which differs from the well known Rouse matrix ($\underline{R} = \underline{A} \; \underline{A}^T$) by the extra operation D^{-1} (6). For a homopolymer, $\underline{D}$ matrix (eq. 3) is a unit matrix so that the $\underline{S}$ matrix is reduced to the $\underline{R}$ matrix. The Rouse model predicts for the latter case a discrete retardations spectrum (11):

$$\tau_p = 1/\sigma\lambda_p = fb^2/3kT\lambda_p \; , \qquad (7)$$

where λ'_ps are the N eigenvalues of the $\underline{R}$ matrix (6):

$$\lambda_p = 4 \sin^2 [p\pi/2(N + 1)] \; , \quad p = 1,2...N. \qquad (8)$$

For graft copolymers, the eigenvalue spectrum of the $\underline{S}$ matrix is readily obtained numerically on a computer by using a subroutine for determining the eigenvalues and eigenvectors of symmetric matrices. Retardation times are then calculated from these eigenvalues using eq. 7. The relaxation times have been shown to be just half of the corresponding retardation times (16).

The computed data are given in terms of normalized relaxation times defined by

$$\tau_p(\text{normalized}) = 1/(N + 1)^2\lambda_p \qquad (9)$$

The use of the normalized relaxation time removes the arbitrariness of the choice of the value of N in the computation of maximum relaxation times. To arrive at eq. 9, we note that $f = m\xi$, where m is the number of monomers per submolecule and ξ is the monomeric friction coefficient, and

that $b^2 \propto m\ell^2$ where ℓ is the length of the monomeric segment.
For a given molecular weight M, $m = M/(N + 1)$. Therefore
the relaxation time (eq. 7) must be inversely proportional to
$(N + 1)^2$. The use of τ_p (normalized), however, does not eliminate
the dependance on N of shorter relaxation times (see eq. 8 for
the case of homopolymers). Maximum relaxation time for a graft
copolymer is normalized by that for a homopolymer as follows:

$$\tau_{max}(\text{normalized}) = \tau_{max\ graft}/\tau_{max\ homopolymer} \qquad (10)$$

For a radial block copolymer, similar equations can be set
up to solve for the relaxation times. A schematic diagram for
such a polymer is shown in Figure 2, which has r branches, each
of which is consisted of g A-beads and m B-beads. The important
distinction here is that beads connected to the radiating center
are pulled by many other beads also attached to the radiating
center. This gives rise to a value r, the number of radiating
chains, at diagonal positions of the matrix $\underline{Z}_r$ corresponding to
these beads, and the value -1 for all off-diagonal elements
representing the interactions between any connected bead-pairs:

$$Z_r = \begin{bmatrix}
-1 & -1 & & & & & & & \\
-1 & 2 & -1 & & & & & & \\
& -1 & 2 & & & & & & \\
& & -1 & r & 0 & & & & \\
& & & 0 & -1 & -1 & & & \\
& & & & -1 & 2 & -1 & & \\
& & & & & -1 & 2 & & \\
& & & & & & -1 & r & 0 \\
& & & & & & & 0 & -1 \\
& & & & & & & & \ddots
\end{bmatrix}$$

Results and Discussion

To facilitate presentation and discussion of the results, the notation used in this work needs to be clarified. A general graft copolymer structure is depicted in Fig. 3, which shows a five-combed graft copolymer where g is the number of beads in the side chain, and m is the number of beads between two adjacent graft points.

The effects of varying the side chain lengths, g, and the spacings between the side chains, m, on the relaxation times have been investigated. Furthermore, the effect of having side chains of verying lengths on a given parent polymer and irregular spacings between adjacent graft points, in contrast to cases with uniform side chain length and regular spacing, has also been examined. In all instances, δ_A was chosen to be 423. This value is obtained from literature data for A-beads of poly(α-methylstyrene) and B-beads of Polystyrene (1). The side chains were assumed to be poly(α-methylstyrene) and the parent polymer polystyrene.

The normalized relaxation times are plotted against the weight percent of polymer B (the backbone polymer, polystyrene) in Figure 4. In computing the weight percent, the value $m_A/m_S = 1.4$ is assumed (1), where m_A, m_S are the number of monomer units per submolecule of poly(α-methylstyrene) and polystyrene, respectively. The effects of introducing grafted chains with a higher friction coefficient are similar to those in the case of block copolymers (11). There is a split in the relaxation spectra, with the maximum relaxation times shifted to higher values.

The computed maximum relaxation times of the graft copolymers were normalized by those of the pure comb-shaped (17) homopolymer, polystyrene, as follows (1):

$$\tau_{max}(\text{normalized}) = \frac{1}{2\sigma_B\lambda_{min}} \Big/ \frac{1}{2\sigma_B\lambda^{\circ}_{min}} = \frac{\lambda^{\circ}_{min}}{\lambda_{min}} \tag{11}$$

where λ_{min} is the smallest of the eigenvalues, and λ°_{min} refers to that of the homopolymer. Table 1 presents calculated data on comb-shaped graft copolymers with different number of side chains (grafts). Fig. 5 exhibits a smooth curve drawn through 35 calculated points of different side chain lengths and graft spacings (and thus different weight compositions). These calculated cases also cover graft copolymers with three to ten side chains. All points follow the representative curve closely with a maximum scatter of less than 0.08 in Log τ_{max}. The difference vanishes as the number of side chains increases. This curve is therefore expected to give a good prediction of the maximum relaxation time behavior for polystyrene grafted with poly(α-methylstyrene) for any given number of side chains.

To further investigate the validity and generality of this computed curve, several other cases were calculated where the side chains were assumed to have different number of beads with the total number of side chain beads remaining constant, i.e., g was not a constant but the sum of all the g's was a constant (weight composition did not change, just the side chain lengths were irregular). Similarly, the number of beads separating the graft points was varied along the main chain, i.e., m was not a constant while the sum of m's was a constant

Finally, both g and m were set as variables. The results are tabulated in Table 2. The maximum relaxation time is seen to be an insensitive function of the distribution of side chain lengths and spacings between graft points. This finding further substantiates our previous conclusion that the maximum relaxation time as a function of graft copolymer composition can be reasonably represented by Fig. 5.

The viscoelastic behavior of radial multichain block copolymer can also be similarly computed. As shown in Fig. 2, g and m are numbers of beads in the poly(α-methylstyrene) and polystyrene blocks respectively. Calculations have been conducted for the case in which g and m are both 4, and the number of chains is 9, as a preliminary attempt to determine if multichain radial block copolymers behave differently from comb-shaped graft copolymers. The results for a polymer containing 41.7% polystyrene are given in Table 3. The normalized maximum relaxation time is $3.921 - 1.360 = 2.561$ in log scale. This result suggests that the behavior of a multichain block copolymer resembles that of ASA triblock copolymer (1,11) where A and S stand for poly(α-methylstyrene) and polystyrene blocks. Here, varying the distributions of g's and m's is seen to result in significant changes in the maximum relaxation times regardless of the fact that the weight composition has been preserved.

Table 4 shows the calculated viscoelastic parameters for 15 multichain radial block copolymers. These block copolymers are star-shaped with branches of equal length. The normalized relaxation times are plotted against the weight percent of styrene

in Figure 6. From the calculated maximum relaxation times of these cases and those of the corresponding branched homopolymers (17), the normalized maximum relaxation time can be plotted as a function of the weight percent of styrene blocks as shown in Fig. 7. A smooth curve can be drawn through all calculated points. This curve shows the same general trend as Fig. 5 but the rise is much sharper as the α-methylstyrene weight content begins to increase. It appears that the end α-methylstyrene blocks are very effective in increasing the maximum relaxation time of the multichain radial block copolymer.

In conclusion, the maximum relaxation times as a function of composition for graft and radial block copolymers have been computed (Figs. 5 and 7). These curves show the relative retardation effectiveness of the higher friction beads placed at different locations in the macromolecules. These beads when grafted onto the side of a linear main chain (lower friction beads) are less effective than those added to the end of the branches of a star-shaped parent polymer. Note that Fig. 7 resembles the ABA curve by Hansen and Shen (1,2) which is to be expected since ABA is the limiting case of the radial block copolymers.

Acknowledgement

References

1. D. R. Hansen and M. Shen, Macromol., $\underline{8}$, 903 (1975).

2. M. Shen and D. R. Hansen, J. Polymer Sci., Part C,
   No. 46, 55 (1974).

3. S. Krause, J. Phys. Chem., $\underline{68}$, 1948 (1964).

4. L. A. Utracki, and R. Simha, Macromolecules, $\underline{1}$, 505 (1968).

5. H. Ohnumba, T. Kotaka and H. Inagaki, Polymer J., $\underline{1}$, 716 (1970).

6. P. E. Rouse, J. Chem. Phys., $\underline{21}$, 1272 (1953).

7. F. Bueche, J. Chem. Phys., $\underline{22}$, 603 (1954).

8. B. Zimm, J. Chem. Phys., $\underline{24}$, 269 (1956).

9. R. E. DeWames, W. F. Hall and M. Shen, J. Chem. Phys.,
   $\underline{46}$, 2782 (1967).

10. M. Shen, W. F. Hall and R. E. DeWames, Rev. Macromol.
    Chem., $\underline{2}$, 183 (1968).

11. D. R. Hansen and M. Shen, Macromolecules, $\underline{8}$, 343 (1975).

12. W. F. Hall and R. E. DeWames, Macromolecules, $\underline{8}$, 349 (1975).

13. W. H. Stockmayer and J. W. Kennedy, Macromolecules, $\underline{8}$,
    351 (1975).

14. F. W. Wang, Macromolecules, $\underline{8}$, 364 (1975).

15. D. Soong and M. Shen, Macromolecules, $\underline{10}$, 357 (1977).

16. W. L. Peticolas, Rubber Chem. Tech., $\underline{36}$, 1422 (1963).

17. D. Soong and M. Shen, to be published.

Table 1. Viscoelastic Parameters of Comb-shaped Graft Copolymers

Number of Grafts	g	m	Log τ_{max}	η_o	J_{eR}
5	1	5	3.734	8.68×10^3	0.442
5	1	7	3.864	1.16×10^4	0.449
5	1	9	3.982	1.51×10^4	0.453
5	1	11	4.075	1.86×10^4	0.456
5	2	5	4.016	1.81×10^4	0.381
5	3	5	4.205	2.99×10^4	0.340
5	4	5	4.343	4.37×10^4	0.310
5	5	5	4.452	5.93×10^4	0.287
5	5	4	4.360	5.08×10^4	0.264
5	5	3	4.244	4.25×10^4	0.236
5	5	2	4.087	3.42×10^4	0.202
5	5	1	3.851	2.59×10^4	0.165
6	1	4	3.751	9.36×10^3	0.413
6	2	4	4.063	2.10×10^4	0.350
6	3	4	4.251	3.49×10^4	0.308
6	4	4	4.388	5.11×10^4	0.277
6	4	3	4.261	4.15×10^4	0.247
6	4	2	4.085	3.19×10^4	0.205
6	4	1	3.791	2.21×10^4	0.151
3	1	5	3.297	2.74×10^3	0.595
3	2	5	3.623	6.48×10^3	0.492
3	3	5	3.829	1.12×10^4	0.437
3	4	5	3.983	1.69×10^4	0.401
3	5	5	4.107	2.37×10^4	0.376
3	5	4	4.033	2.08×10^4	0.355
3	5	3	3.943	1.80×10^4	0.330
3	5	2	3.834	1.53×10^4	0.303
3	5	1	3.699	9.23×10^3	0.275
10	1	3	4.049	1.92×10^4	0.378
10	2	3	4.357	4.25×10^4	0.322
10	3	3	4.540	6.91×10^4	0.281
10	3	2	4.342	4.93×10^4	0.235
10	3	1	3.974	2.86×10^4	0.148

Table 2. Viscoelastic Parameters of Graft Copolymers
with a Distribution of Side Chain Lengths, g,
and Spacing Between Graft Points, m.

g	m	Log τ_{max}	η_o	J_{eR}
5,5,5,5,5	all 5's	4.452	5.93×10^4	0.287
4,3,5,11,2	all 5's	4.461	5.78×10^4	0.301
4,1,10,9,1	all 5's	4.390	5.73×10^4	0.287
5,4,7,2,7	all 5's	4.494	6.25×10^4	0.315
4,7,6,6,2	all 5's	4.381	5.53×10^4	0.258
all 5's	11,8,1,1,4	4.525	6.00×10^4	0.356
all 5's	17,4,1,1,2	4.550	6.00×10^4	0.383
all 5's	7,9,1,1,7	4.492	5.60×10^4	0.349
13,1,7,1,3	6,3,5,10,1	4.596	7.03×10^4	0.367
4,4,5,7,5	1,6,5,2,11	4.393	5.00×10^4	0.298
10,9,1,1,4	3,12,4,5,1	4.575	7.10×10^4	0.356

Table 3. Effects of Distribution of Block Lengths, g, m, on the Viscoelastic Parameters of Radial Block Copolymers (Number of chains = 9)

g	m	Log τ_{max}	η_o	J_{eR}
all 4's	all 4's	3.921	7.52×10^4	0.0993
5,10,1	all 4's	4.395	8.24×10^4	0.155
1,3,6				
3,5,2				
all 4's	13,9,1			
	1,1,1	4.346	7.73×10^4	0.161
	1,7,2			
1,1,7	5,1,3			
5,6,4	18,2,3	4.564	8.74×10^4	0.225
2,7,3	1,1,2			

Table 4. Viscoelastic Parameters of Multichain Radial
Block Copolymers

Number of Branches	g	m	Log τ_{max}	η_o	J_{eR}
5	1	5	3.344	8.86×10^3	0.248
5	1	7	3.486	1.23×10^4	0.247
5	1	9	3.593	1.58×10^4	0.247
5	1	11	3.679	1.92×10^4	0.246
5	2	5	3.665	1.96×10^4	0.224
5	3	5	3.866	3.21×10^4	0.211
5	4	5	4.016	4.65×10^4	0.201
5	5	5	4.138	6.27×10^4	0.193
5	5	4	4.066	5.42×10^4	0.187
5	5	3	3.982	4.57×10^4	0.178
5	5	2	3.878	3.72×10^4	0.168
5	5	1	3.748	2.88×10^3	0.156
3	1	5	3.355	4.55×10^3	0.495
3	2	5	3.676	1.01×10^4	0.440
3	3	5	3.876	1.67×10^4	0.408
3	4	5	4.026	2.42×10^4	0.386
3	5	5	4.146	3.28×10^4	0.369
3	5	4	4.076	2.85×10^4	0.354
3	5	3	3.994	2.43×10^4	0.335
3	5	2	3.893	2.00×10^4	0.312
3	5	1	3.767	1.58×10^4	0.284
10	1	3	3.118	1.18×10^4	0.111
10	2	3	3.455	2.77×10^4	0.0962
10	3	3	3.673	4.74×10^4	0.0893
10	3	2	3.539	3.60×10^4	0.0844
10	3	1	3.353	2.46×10^4	0.0775
3	1	15	3.817	1.33×10^4	0.486

18.

Figure Captions

Figure 1. Modelling of a graft point. Bead k experiences forces from beads i, j and l, and vice versa.

Figure 2. Schematic diagram of a radial multichain block copolymer where g is the number of poly(α-methylstyrene) beads, and m is the number of polystyrene beads in the respective blocks.

Figure 3. Schematic diagram of a graft copolymer with 5 grafts along the parent chain. g is the number of beads in the side chains. m is the number of beads of the section separating two adjacent graft points.

Figure 4. Normalized relaxation time spectra for a series of comb-shaped graft copolymers with varying PS contents.

Figure 5. Normalized maximum relaxation time as a function of weight percentage of styrene for polymers of styrene grafted with poly(α-methylstyrene). Circles are calculated points.

Figure 6. Normalized relaxation time spectra for a series of radial block copolymers with varying PS contents.

Figure 7. Normalized maximum relaxation time as a function of weight percentage of styrene for multichain radial block copolymers with α-methylstyrene end blocks. Circles are calculated points.
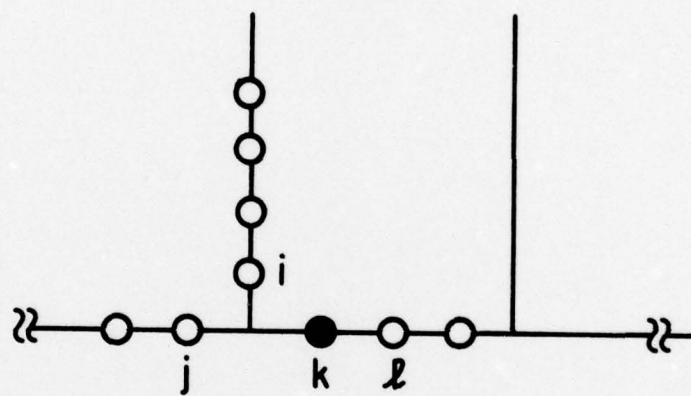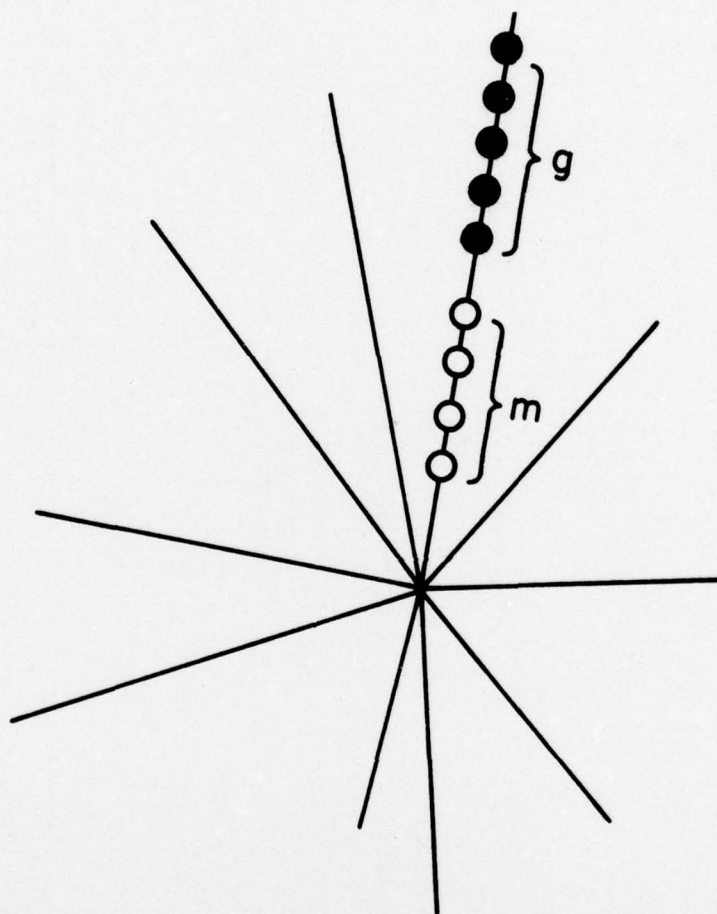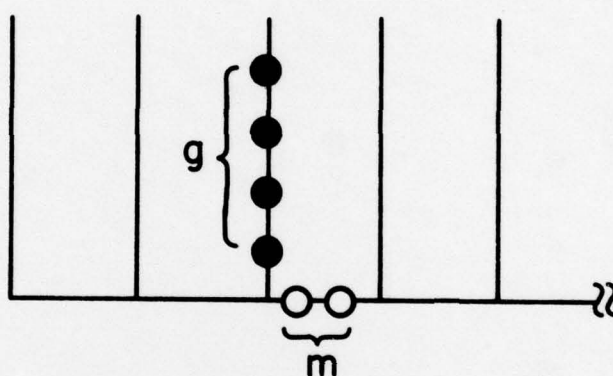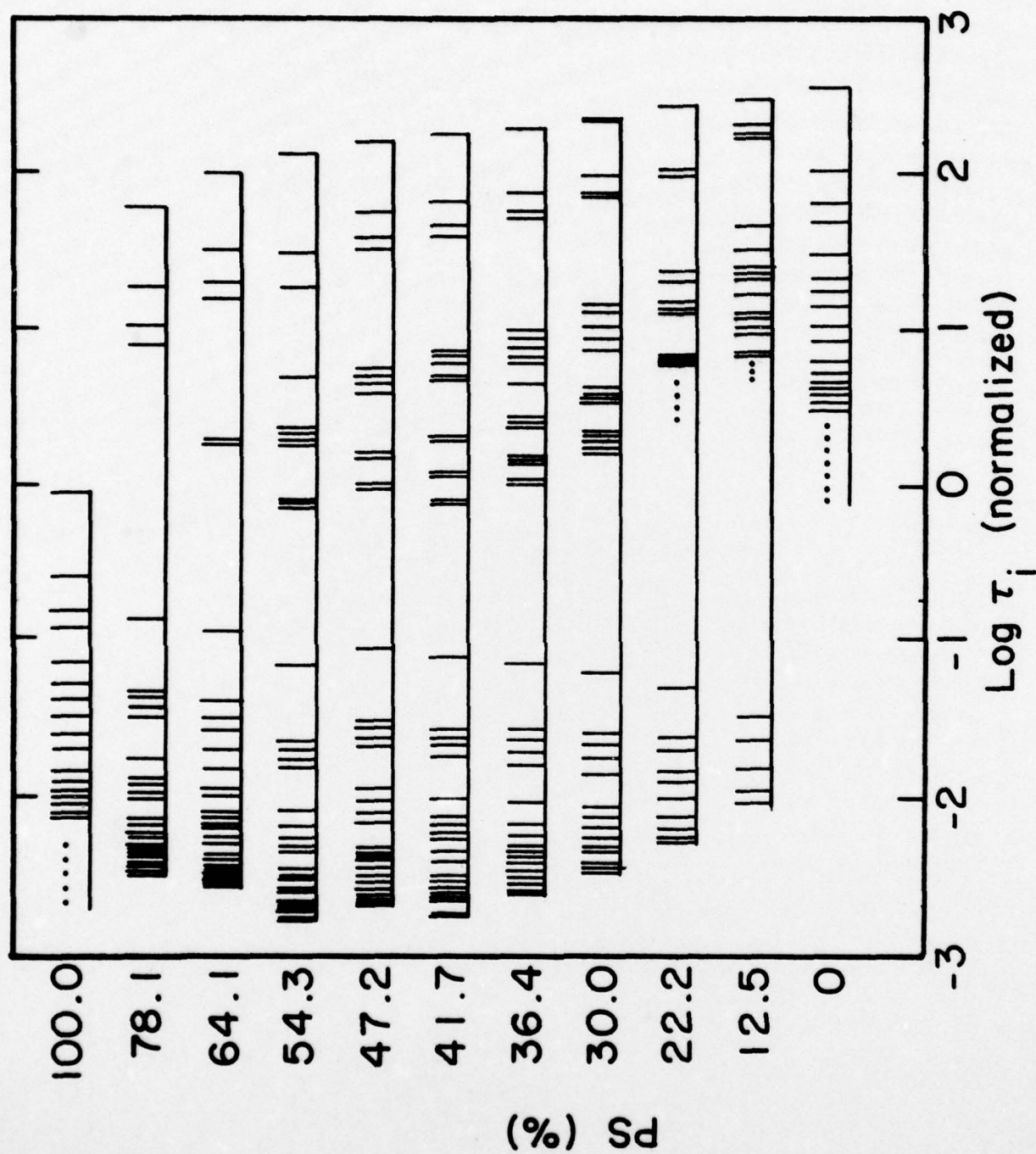
Figure 1

Figure 2

Figure 3

Figure 4
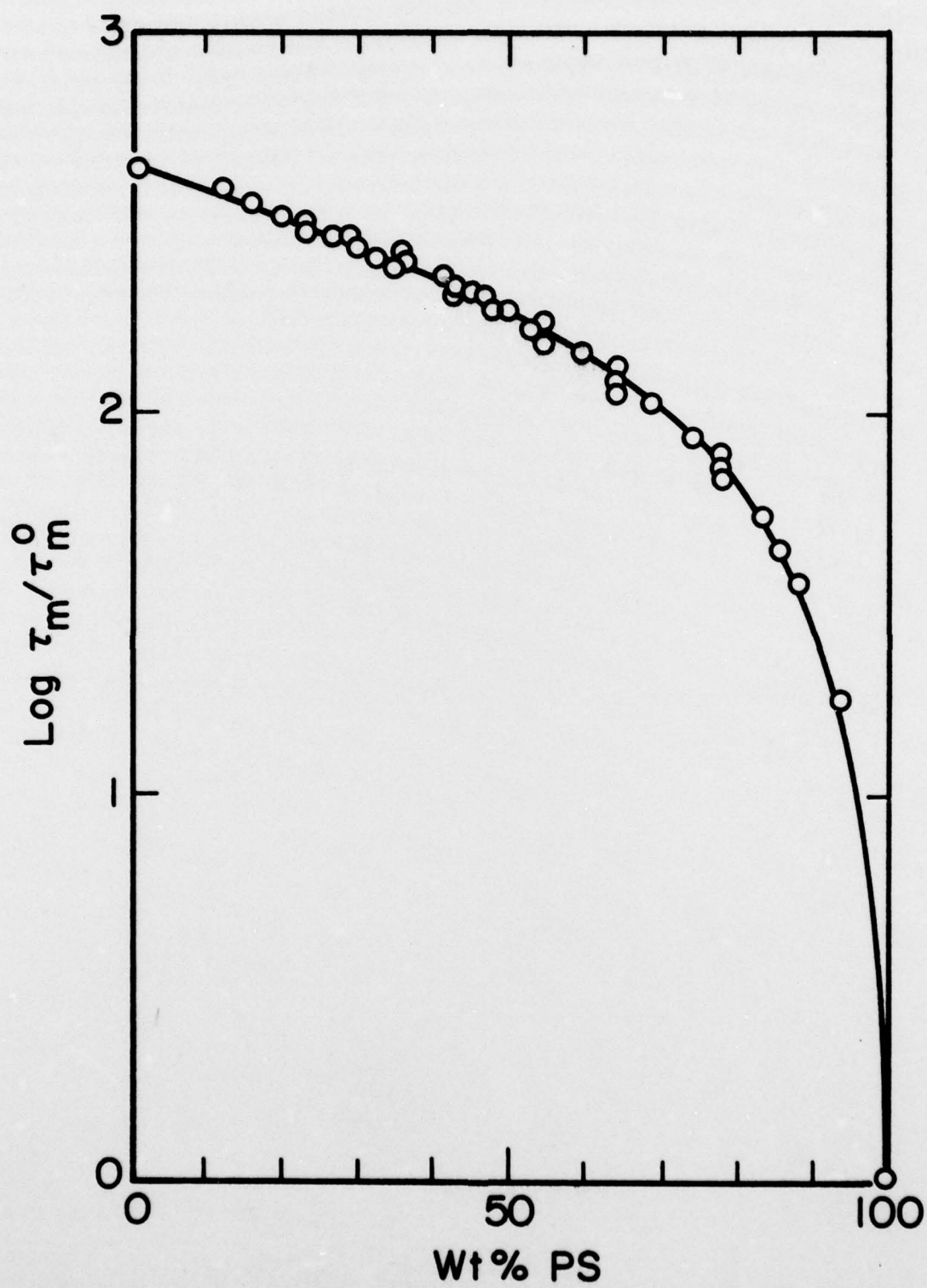
Figure 5
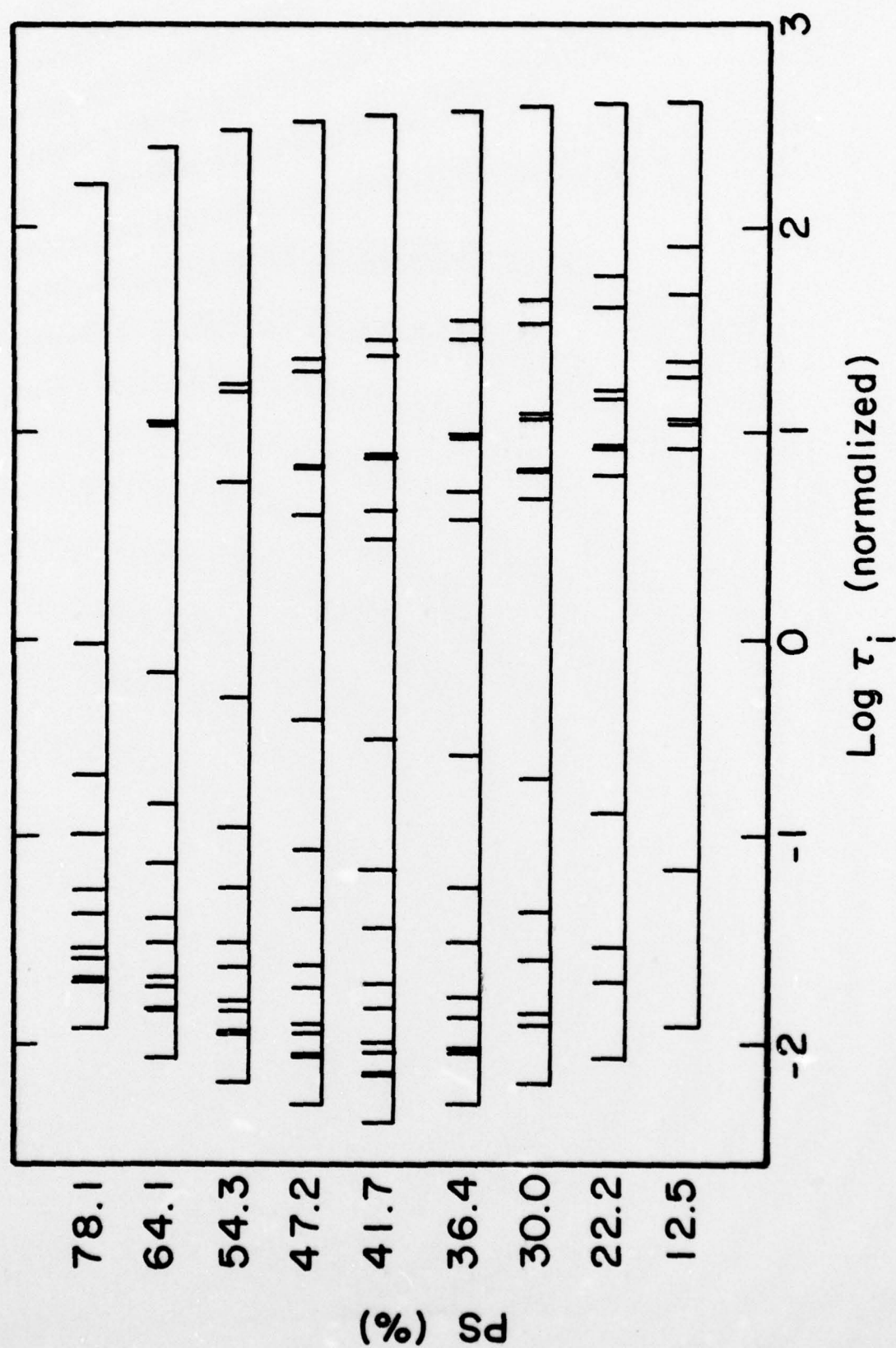
Figure 6
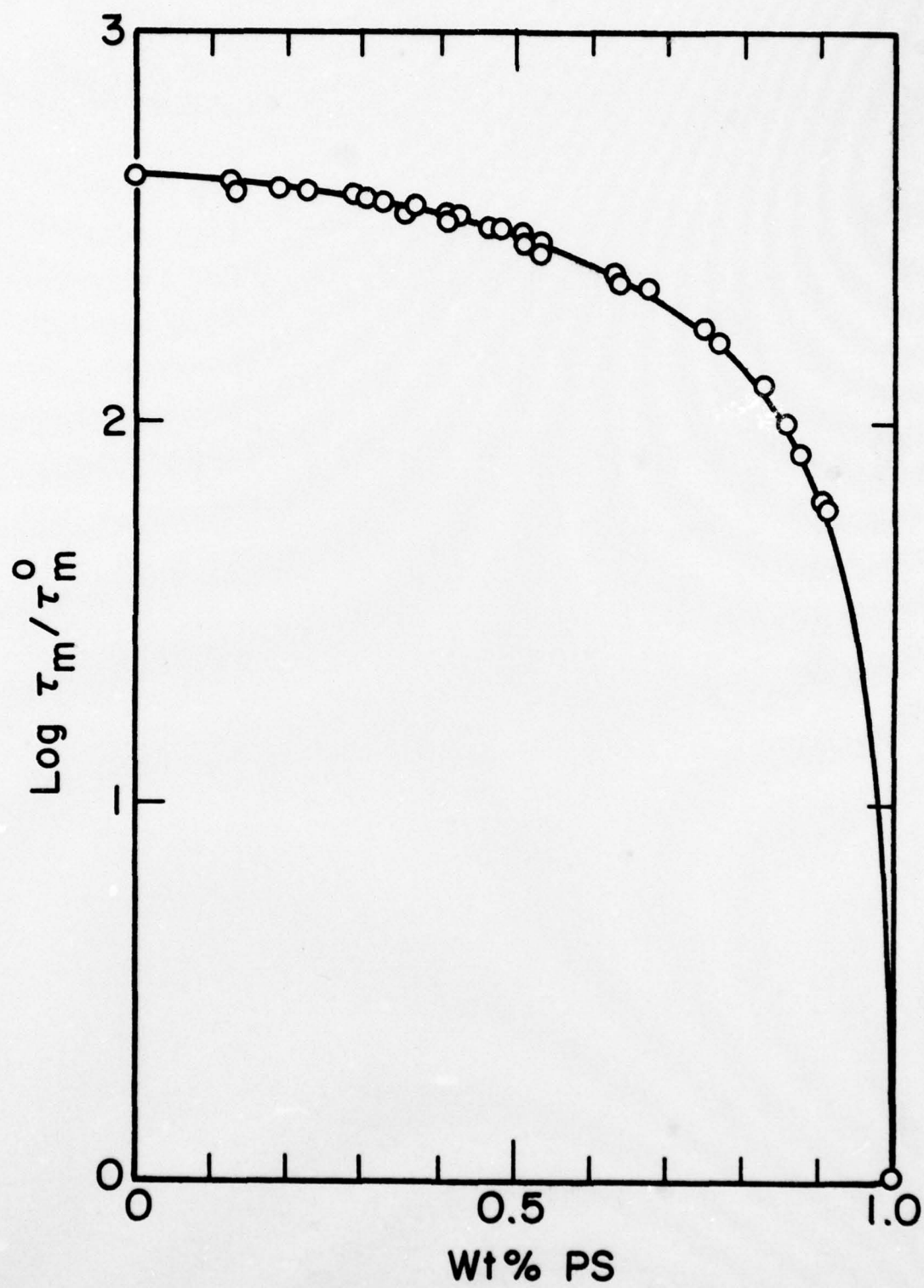
Figure 7

TECHNICAL REPORT DISTRIBUTION LIST, GEN

	No. Copies		No. Copies
Office of Naval Research 800 North Quincy Street Arlington, Virginia 22217 Attn: Code 472	2	Defense Documentation Center Building 5, Cameron Station Alexandria, Virginia 22314	12
ONR Branch Office 536 S. Clark Street Chicago, Illinois 60605 Attn: Dr. George Sandoz	1	U.S. Army Research Office P.O. Box 1211 Research Triangle Park, N.C. 27709 Attn: CRD-AA-IP	1
ONR Branch Office 715 Broadway New York, New York 10003 Attn: Scientific Dept.	1	Naval Ocean Systems Center San Diego, California 92152 Attn: Mr. Joe McCartney	1
ONR Branch Office 1030 East Green Street Pasadena, California 91106 Attn: Dr. R. J. Marcus	1	Naval Weapons Center China Lake, California 93555 Attn: Dr. A. B. Amster Chemistry Division	1
ONR Area Office One Hallidie Plaza, Suite 601 San Francisco, California 94102 Attn: Dr. P. A. Miller	1	Naval Civil Engineering Laboratory Port Hueneme, California 93401 Attn: Dr. R. W. Drisko	1
ONR Branch Office Building 114, Section D 666 Summer Street Boston, Massachusetts 02210 Attn: Dr. L. H. Peebles	1	Professor K. E. Woehler Department of Physics & Chemistry Naval Postgraduate School Monterey, California 93940	1
Director, Naval Research Laboratory Washington, D.C. 20390 Attn: Code 6100	1	Dr. A. L. Slafkosky Scientific Advisor Commandant of the Marine Corps (Code RD-1) Washington, D.C. 20380	1
The Assistant Secretary of the Navy (R,E&S) Department of the Navy Room 4E736, Pentagon Washington, D.C. 20350	1	Office of Naval Research 800 N. Quincy Street Arlington, Virginia 22217 Attn: Dr. Richard S. Miller	1
Commander, Naval Air Systems Command Department of the Navy Washington, D.C. 20360 Attn: Code 310C (H. Rosenwasser)	1	Naval Ship Research and Development Center Annapolis, Maryland 21401 Attn: Dr. G. Bosmajian Applied Chemistry Division	1
		Naval Ocean Systems Center San Diego, California 91232 Attn: Dr. S. Yamamoto, Marine Sciences Division	1

Encl 1

TECHNICAL REPORT DISTRIBUTION LIST, 356A

	No. Copies		No. Copies

Dr. Stephen H. Carr
Department of Materials Science
Northwestern University
Evanston, Illinois 60201   1

Dr. M. Broadhurst
Bulk Properties Section
National Bureau of Standards
U.S. Department of Commerce
Washington, D.C. 20234   2

Dr. T. A. Litovitz
Department of Physics
Catholic University of America
Washington, D.C. 20017   1

Dr. R. V. Subramanian
Washington State University
Department of Materials Science
Pullman, Washington 99163   1

Dr. M. Shen
Department of Chemical Engineering
University of California
Berkeley, California 94720   1

Dr. V. Stannett
Department of Chemical Engineering
North Carolina State University
Raleigh, North Carolina 27607   1

Dr. D. R. Uhlmann
Department of Metallurgy and Material
 Science
Center for Materials Science and
 Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139   1

Naval Surface Weapons Center
White Oak
Silver Spring, Maryland 20910
Attn: Dr. J. M. Augl
 Dr. B. Hartman   1

Dr. G. Goodman
Globe Union Incorporated
5757 North Green Bay Avenue
Milwaukee, Wisconsin 53201   1

Picatinny Arsenal
SMUPA-FR-M-D
Dover, New Jersey 07801
Attn: A. M. Anzalone
 Building 3401   1

Dr. J. K. Gillham
Princeton University
Department of Chemistry
Princeton, New Jersey 08540   1

Douglas Aircraft Co.
3855 Lakewood Boulevard
Long Beach, California 90846
Attn: Technical Library
 Cl 290/36-84
 AUTO-Sutton   1

Dr. E. Baer
Department of Macromolecular Science
Case Western Reserve University
Cleveland, Ohio 44106   1

Dr. K. D. Pae
Department of Mechanics and
 Materials Science
Rutgers University
New Brunswick, New Jersey 08903   1

NASA-Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135
Attn: Dr. T. T. Serofini, MS-49-1   1

Dr. Charles H. Sherman, Code TD 121
Naval Underwater Systems Center
New London, Connecticut   1

Dr. William Risen
Department of Chemistry
Brown University
Providence, Rhode Island 02192   1

Dr. Alan Gent
Department of Physics
University of Akron
Akron, Ohio 44304   1

40

72:GAN:716:tam
78u472-608

TECHNICAL REPORT DISTRIBUTION LIST, 356A

	No. Copies		No. Copies
Mr. Robert W. Jones Advanced Projects Manager Hughes Aircraft Company Mail Station D 132 Culver City, California 90230	1	Dr. T. J. Reinhart, Jr., Chief Composite and Fibrous Materials Branch Nonmetallic Materials Division Department of the Air Force Air Force Materials Laboratory (AFSC) Wright-Patterson Air Force Base, Ohio 45433	1
Dr. C. Giori IIT Research Institute 10 West 35 Street Chicago, Illinois 60616	1	Dr. J. Lando Department of Macromolecular Science Case Western Reserve University Cleveland, Ohio 44106	
Dr. M. Litt Department of Macromolecular Science Case Western Reserve University Cleveland, Ohio 44106	1	Dr. J. White Chemical and Metallurgical Engineering University of Tennessee Knoxville, Tennessee 37916	1
Dr. R. S. Roe Department of of Materials Science and Metallurgical Engineering University of Cincinnati Cincinnati, Ohio 45221	1	Dr. J. A. Manson Materials Research Center Lehigh University Bethlehem, Pennsylvania 18015	1
Dr. L. E. Smith U.S. Department of Commerce National Bureau of Standards Stability and Standards Washington, D.C. 20234	1	Dr. R. F. Helmreich Contract RD&E Dow Chemical Co. Midland, Michigan 48640	1
Dr. Robert E. Cohen Chemical Engineering Department Massachusetts Institute of Technology Cambridge, Massachusetts 02139	1	Dr. R. S. Porter University of Massachusetts Department of Polymer Science and Engineering Amherst, Massachusetts 01002	1
Dr. David Roylance Department of Materials Science and Engineering Massachusetts Institute of Technology Cambridge, Massachusetts 02039	1	Professor Garth Wilkes Department of Chemical Engineering Virginia Polytechnic Institute and State University Blacksburg, Virginia 24061	1
Dr. T. P. Conlon, Jr., Code 3622 Sandia Laboratories Sandia Corporation Albuquerque, New Mexico	1	Dr. Kurt Baum Fluorochem Inc. 6233 North Irwindale Avenue Azuza, California 91702	1
Dr. Martin Kaufmann, Head Materials Research Branch, Code 4542 Naval Weapons Center China Lake, California 93555	1	Professor C. S. Paik Sung Department of Materials Sciences and Engineering Massachusetts Institute of Technology Cambridge, Massachusetts 02139	1

2